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(54) CARBON NANOTUBE DIODES AND ELECTROSTATIC DISCHARGE CIRCUITS AND METHODS

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H01L 51/30 (2006.01)

(52) **U.S. Cl.** **257/653**; 257/E51.04; 977/750

(58) **Field of Classification Search** 257/E51.04
See application file for complete search history.

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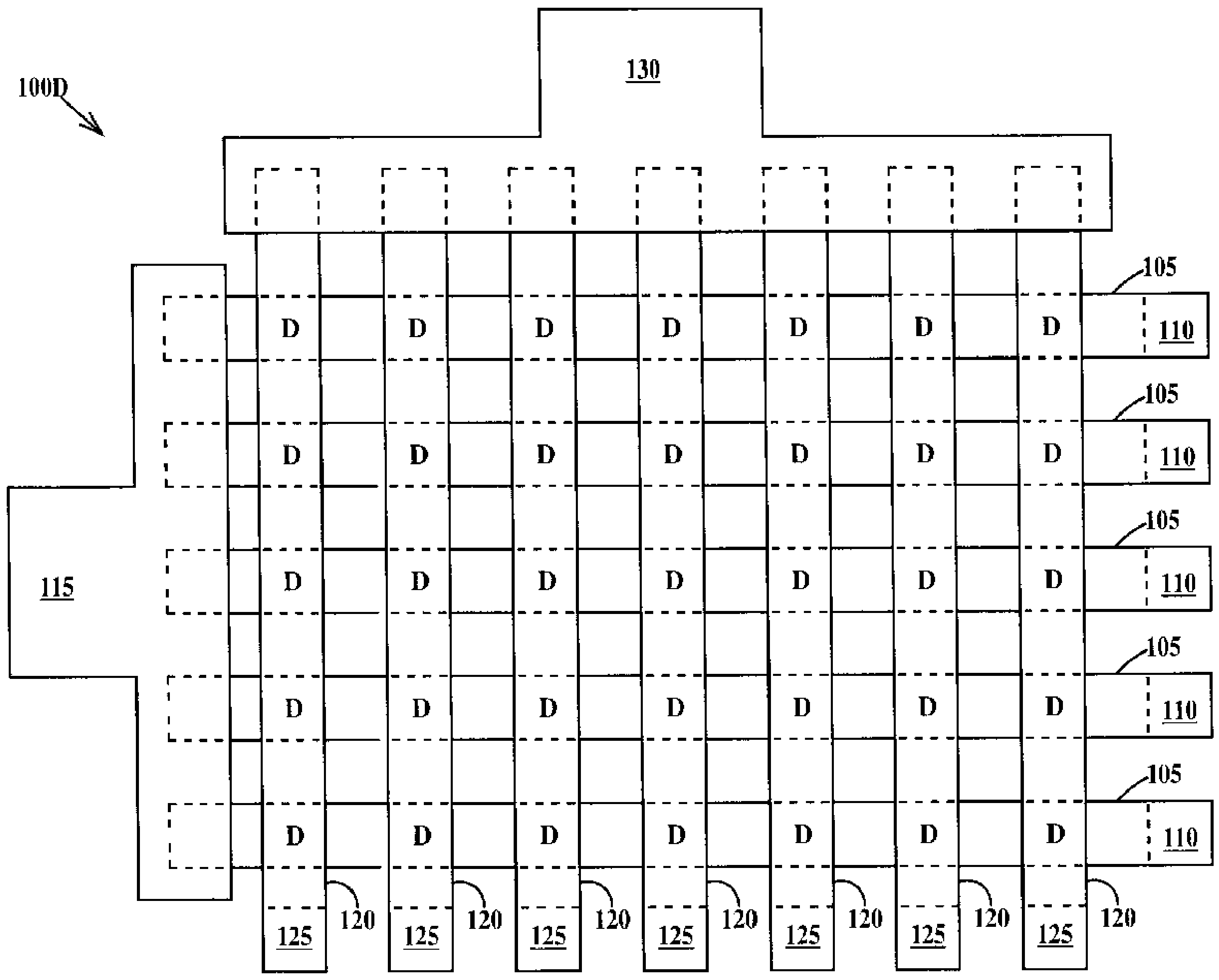
(57) ABSTRACT

Diodes and method of fabricating diodes. A diode includes: an p-type single wall carbon nanotube; an n-type single wall carbon nanotube, the p-type single wall carbon nanotube in physical and electrical contact with the n-type single wall carbon nanotube; and a first metal pad in physical and electrical contact with the p-type single wall carbon nanotube and a second metal pad in physical and electrical contact with the n-type single wall carbon nanotube.

20 Claims, 7 Drawing Sheets



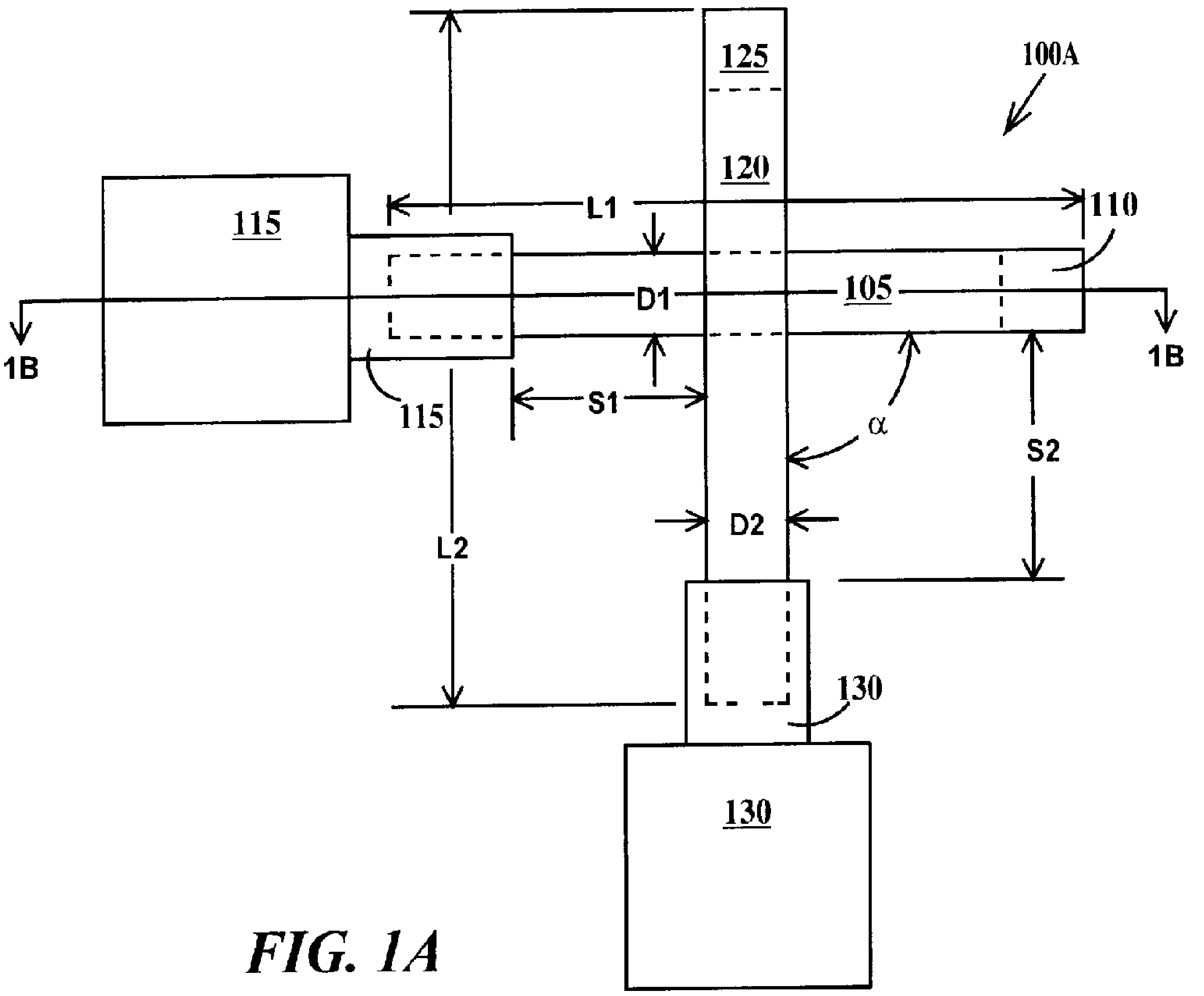

125
100A
120
115
L1
110
D1
105
1B
1B
115
S1
α
S2
D2
L2
130
130

FIG. 1A

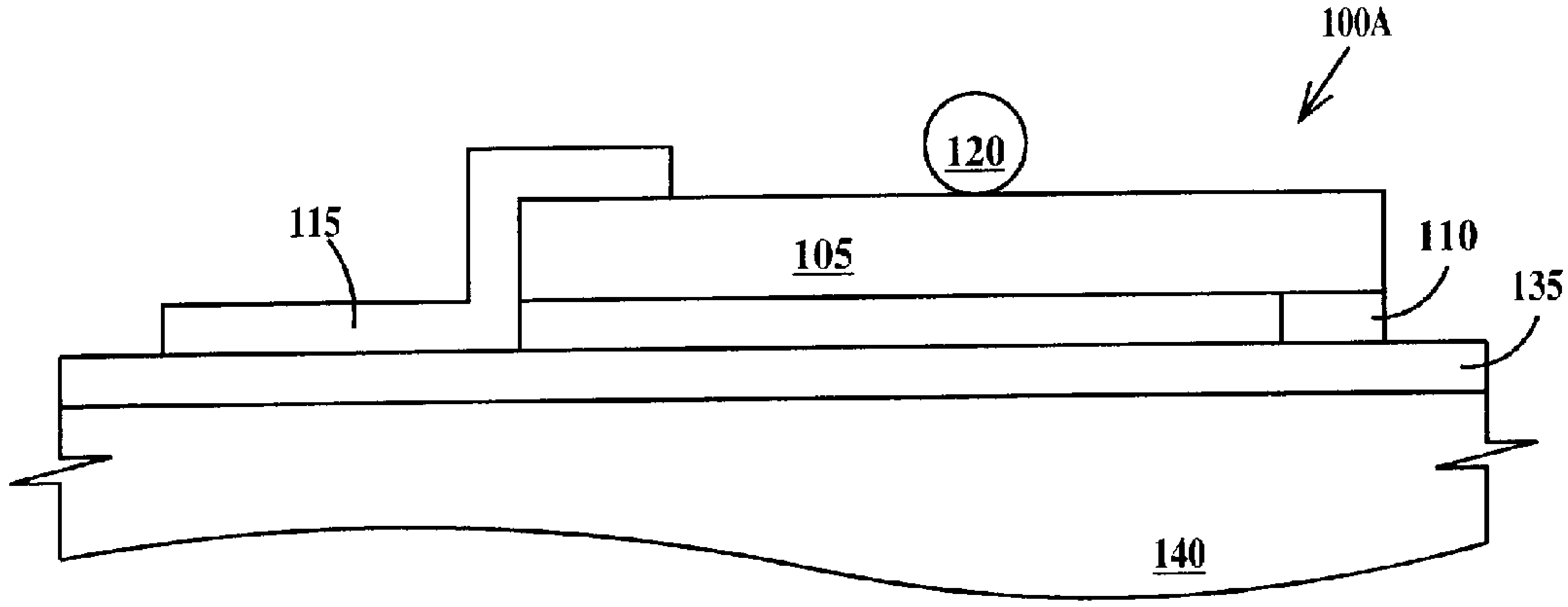

100A
120
115
105
110
135
140

FIG. 1B

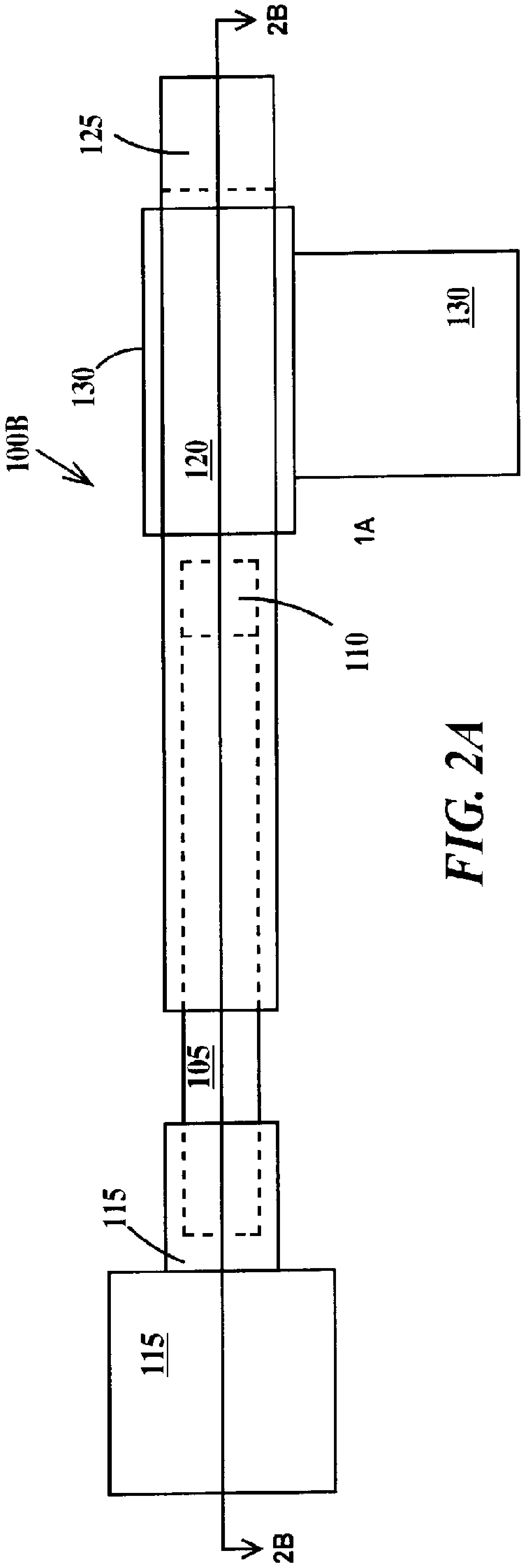

2B
125
130
100B
130
120
1A
110
105
115
115
2B

FIG. 2A

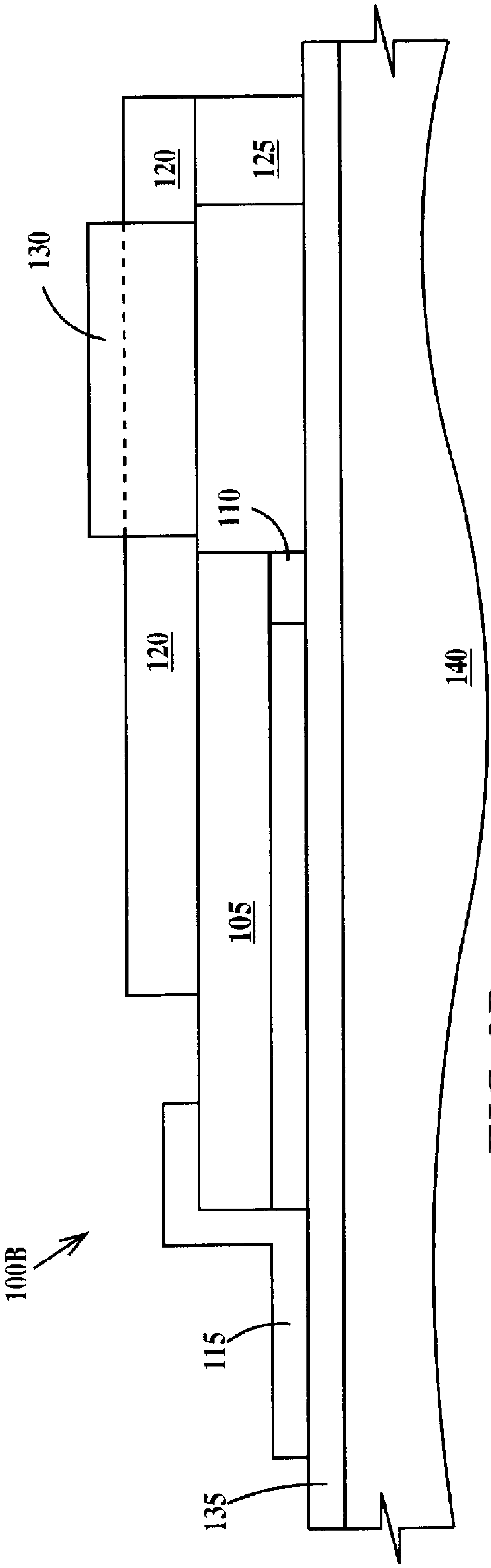

130
120
125
110
120
105
140
100B
115
135

FIG. 2B

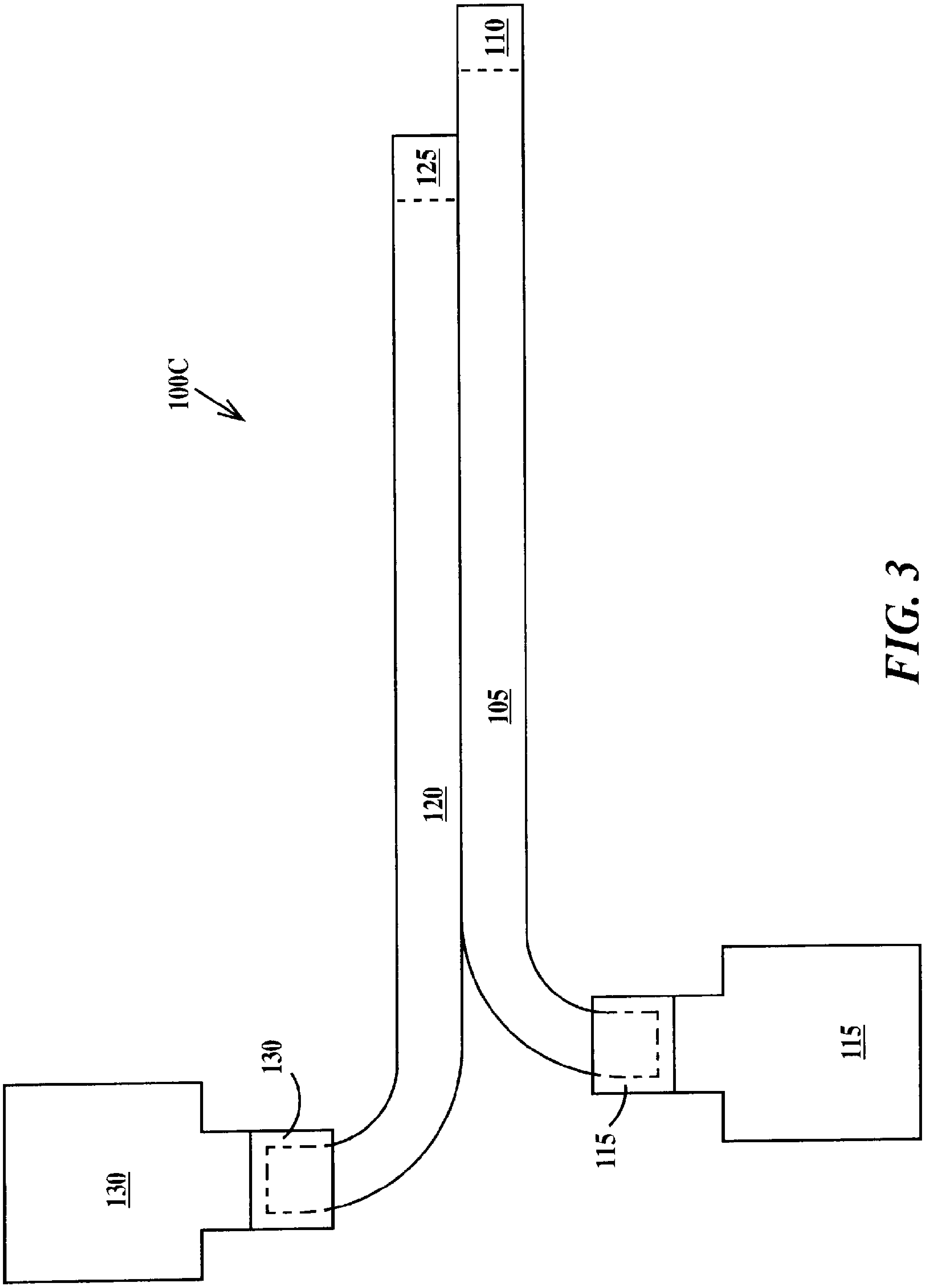


FIG. 3

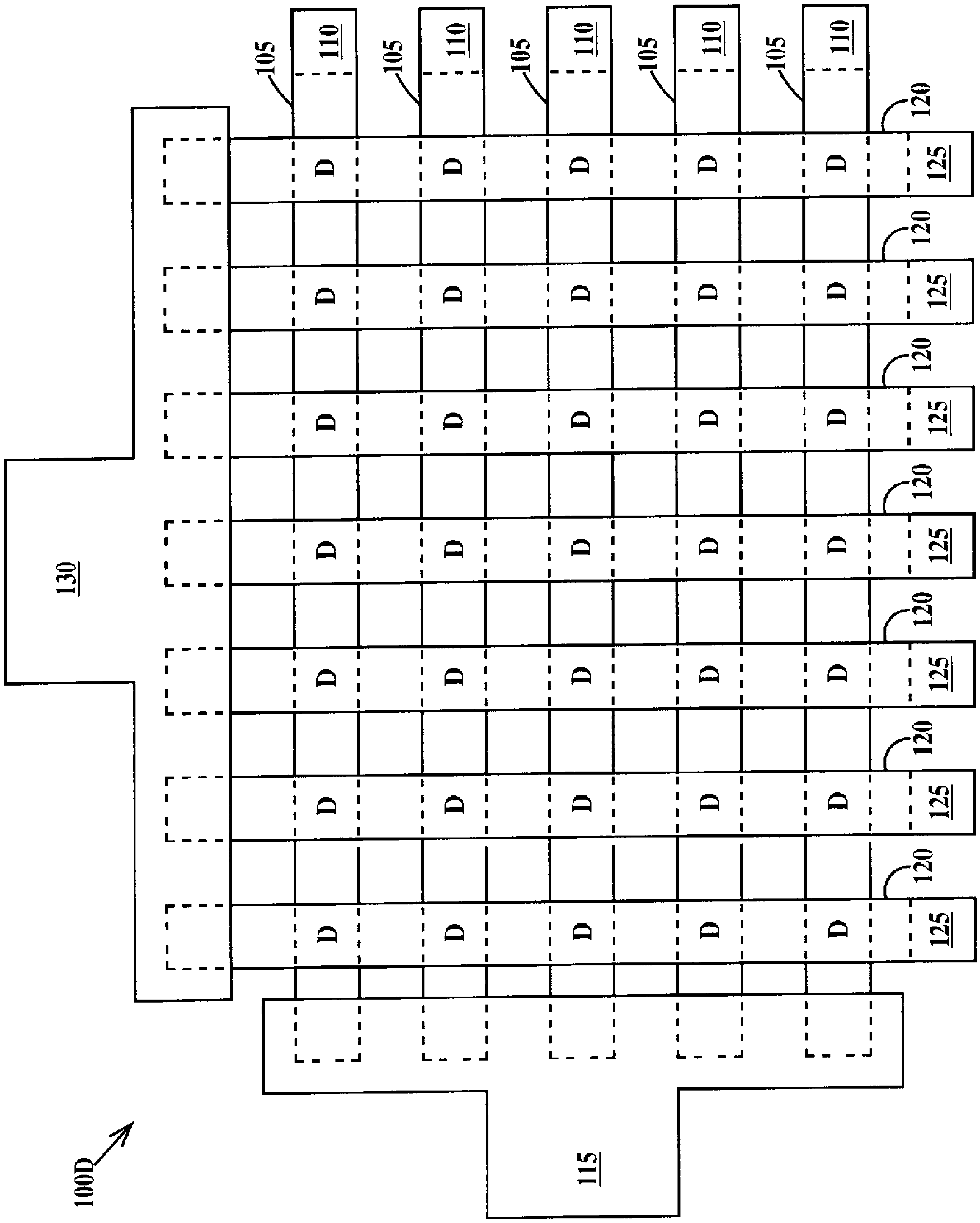
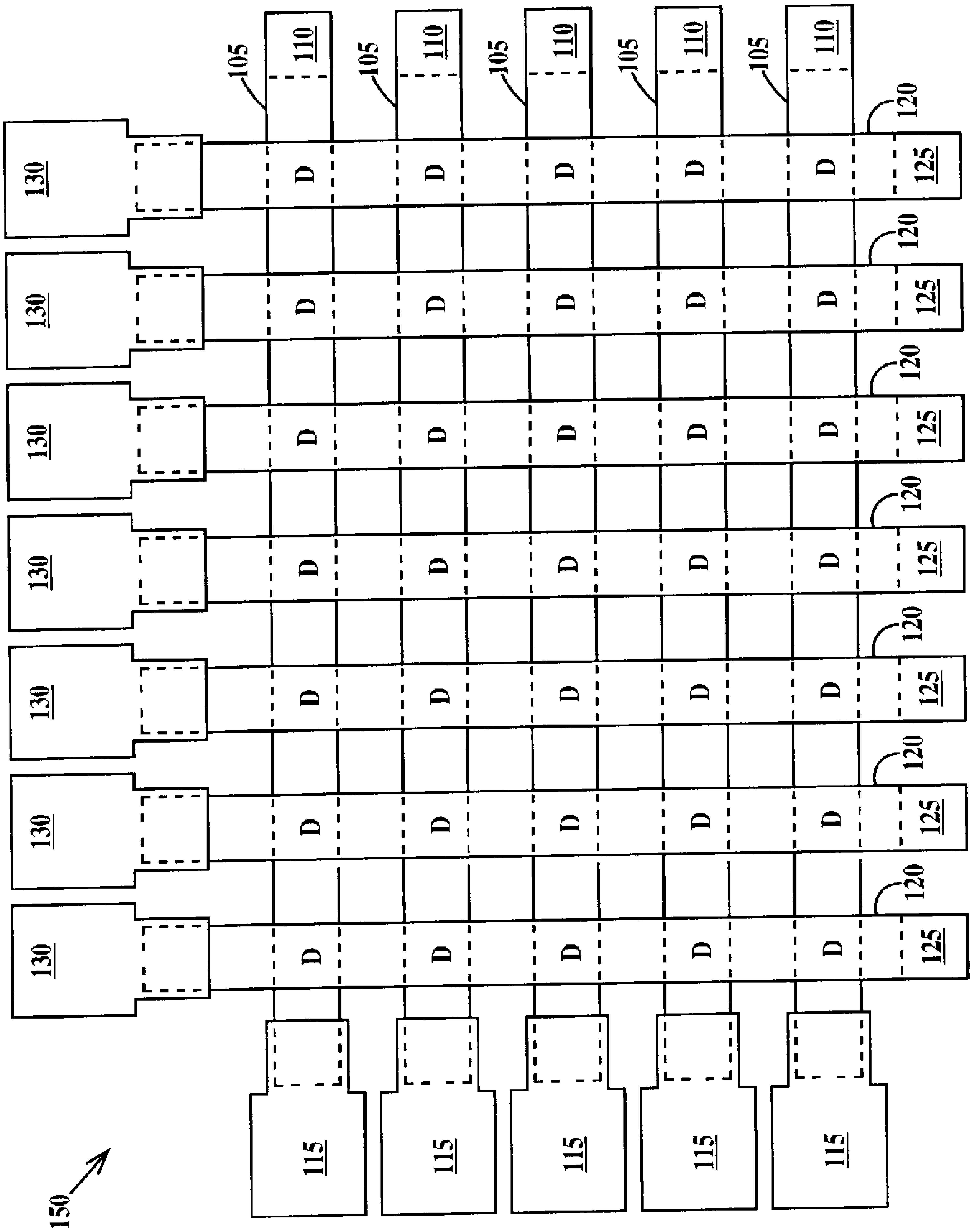


FIG. 4


105
110
105
110
105
110
105
110
105
110
120
125
120
125
120
125
120
125
120
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120
125
120
125
130
130
130
130
130
130
130
D
D
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D
D
D
D
D
D
D
D
D
D
D
D
D
D
D
D
D
D
D
D
D
115
115
115
115
115
150

FIG. 5

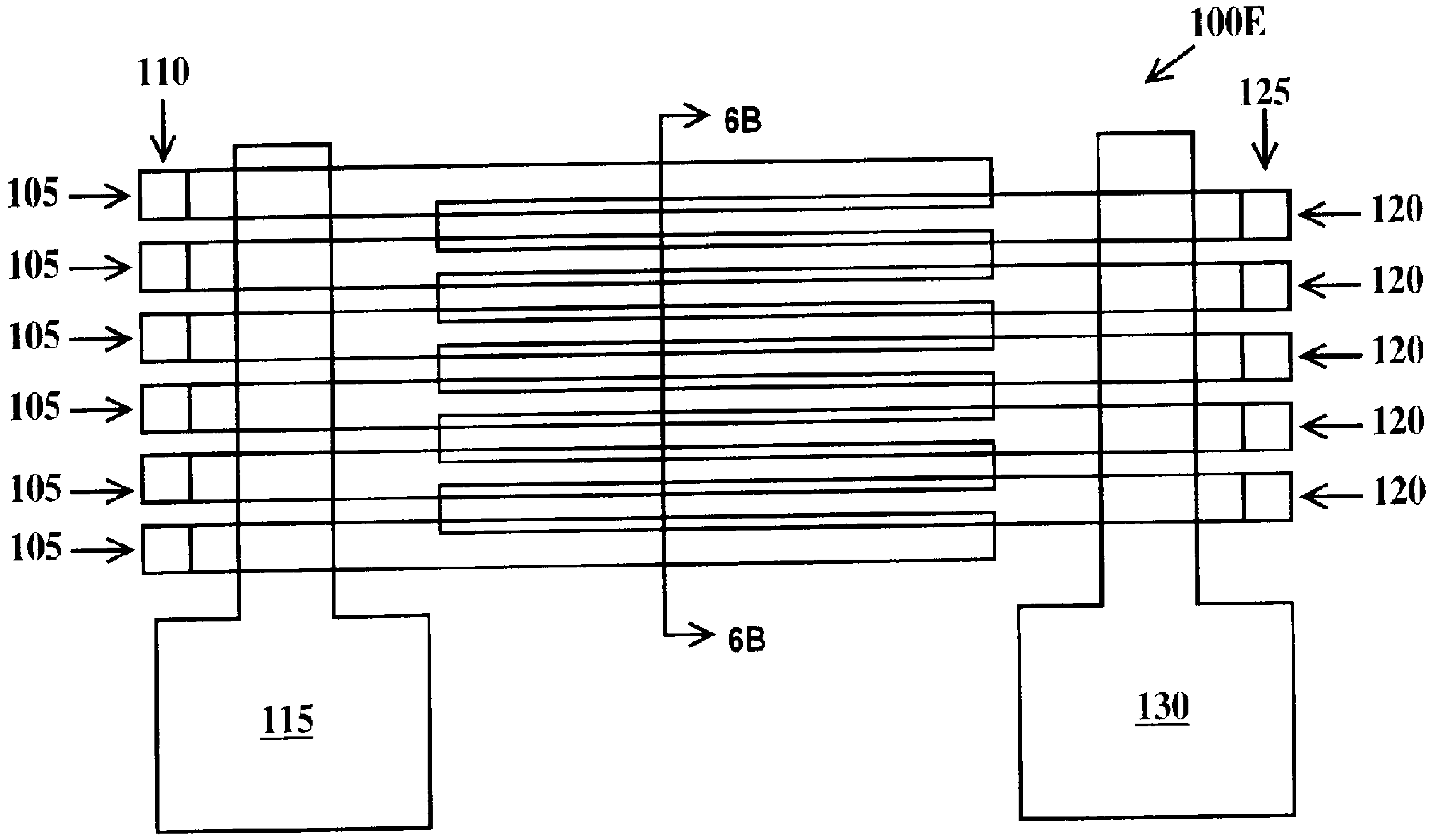

FIG. 6A

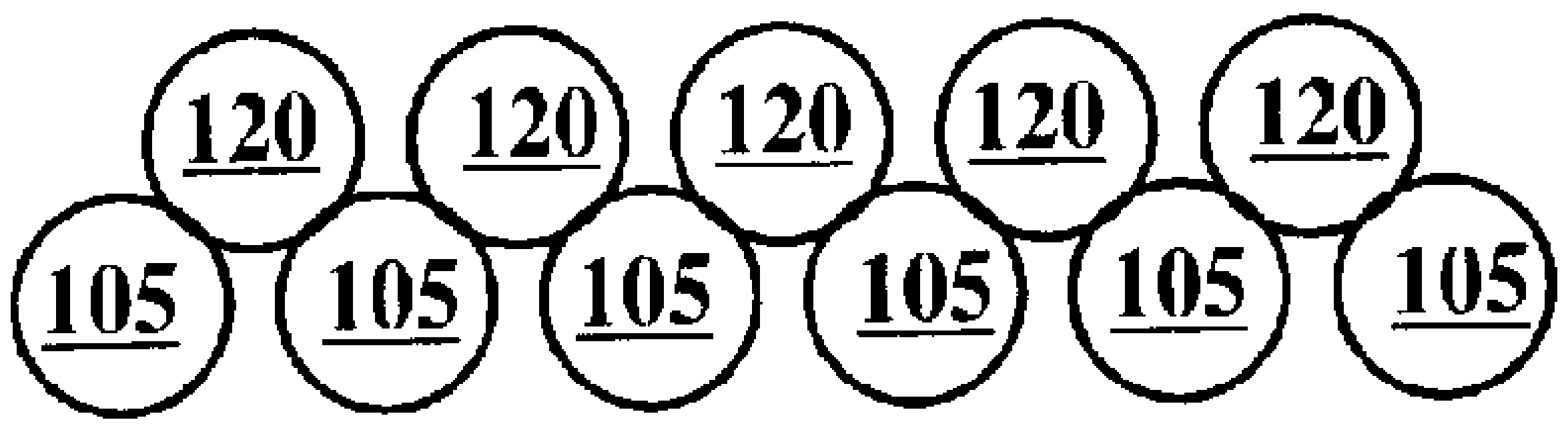

FIG. 6B

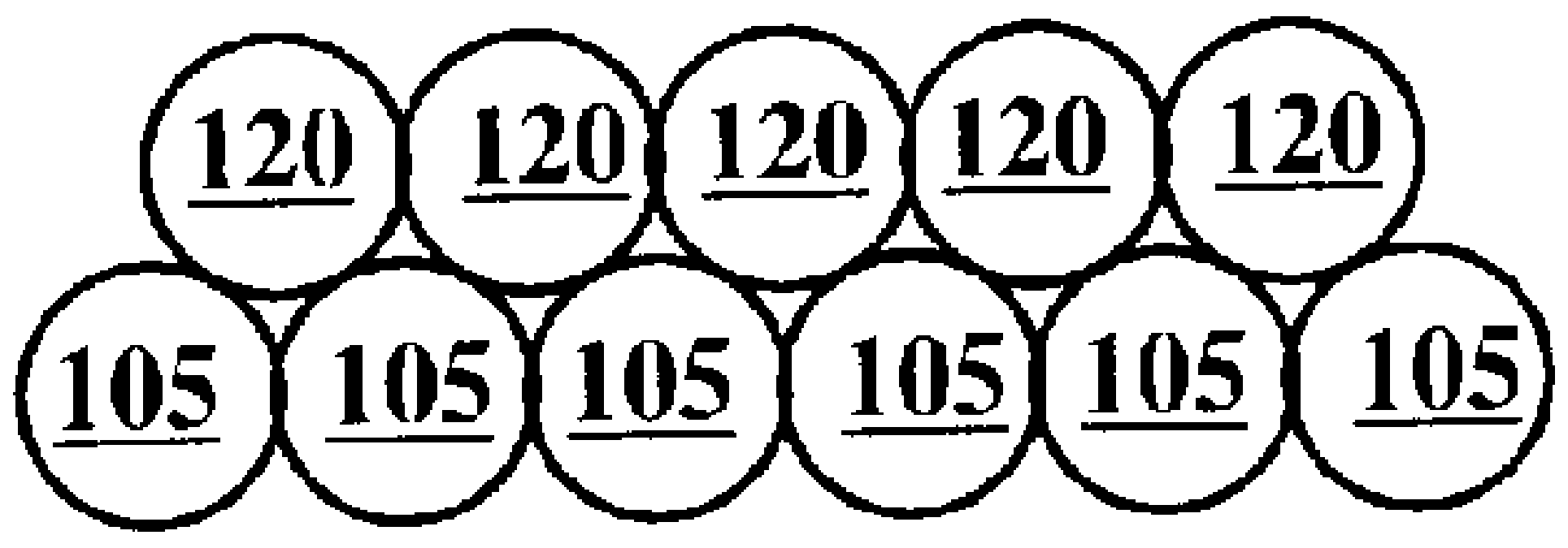

FIG. 6C

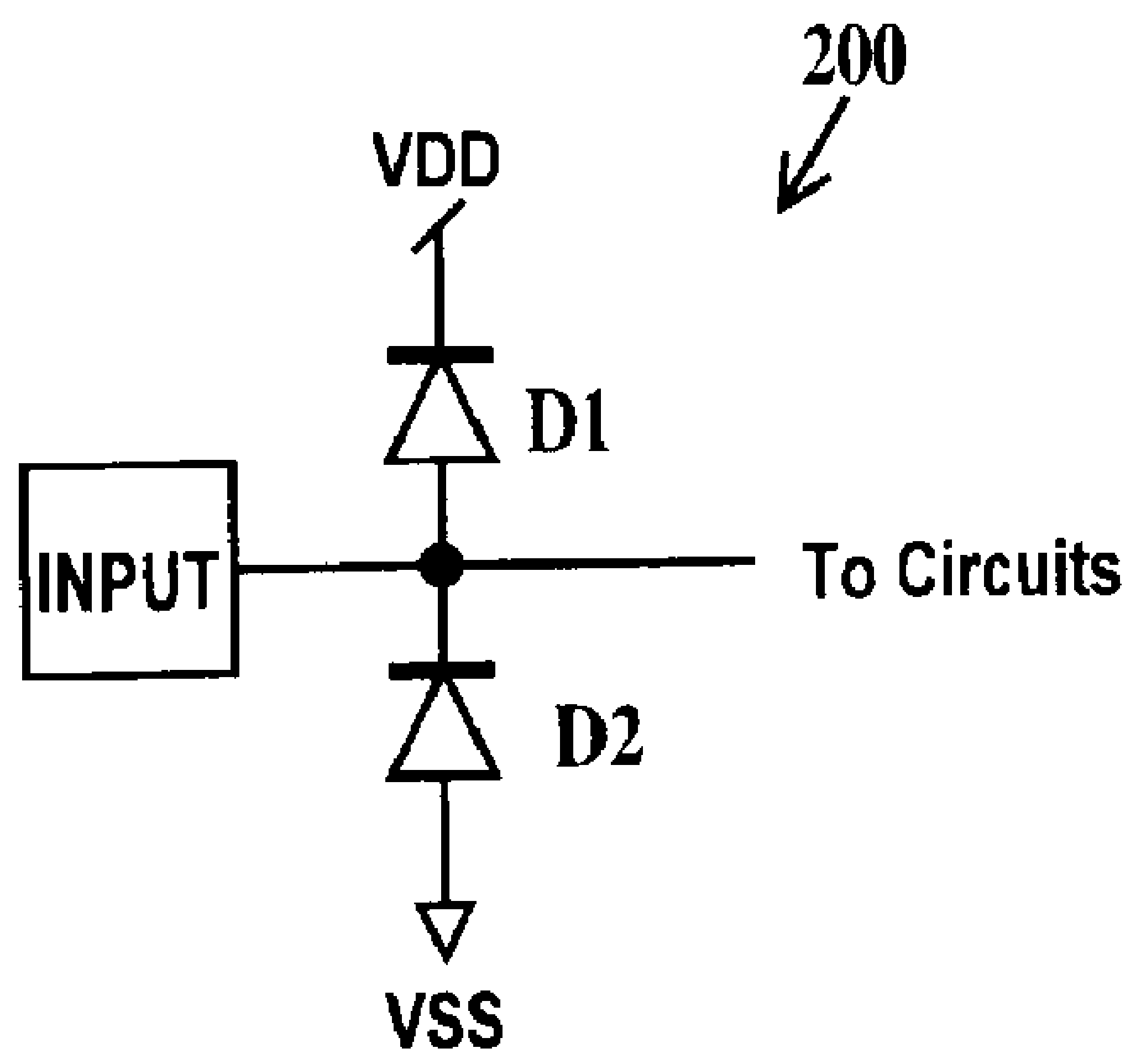
200
VDD
D1
INPUT
To Circuits
D2
VSS

FIG. 7

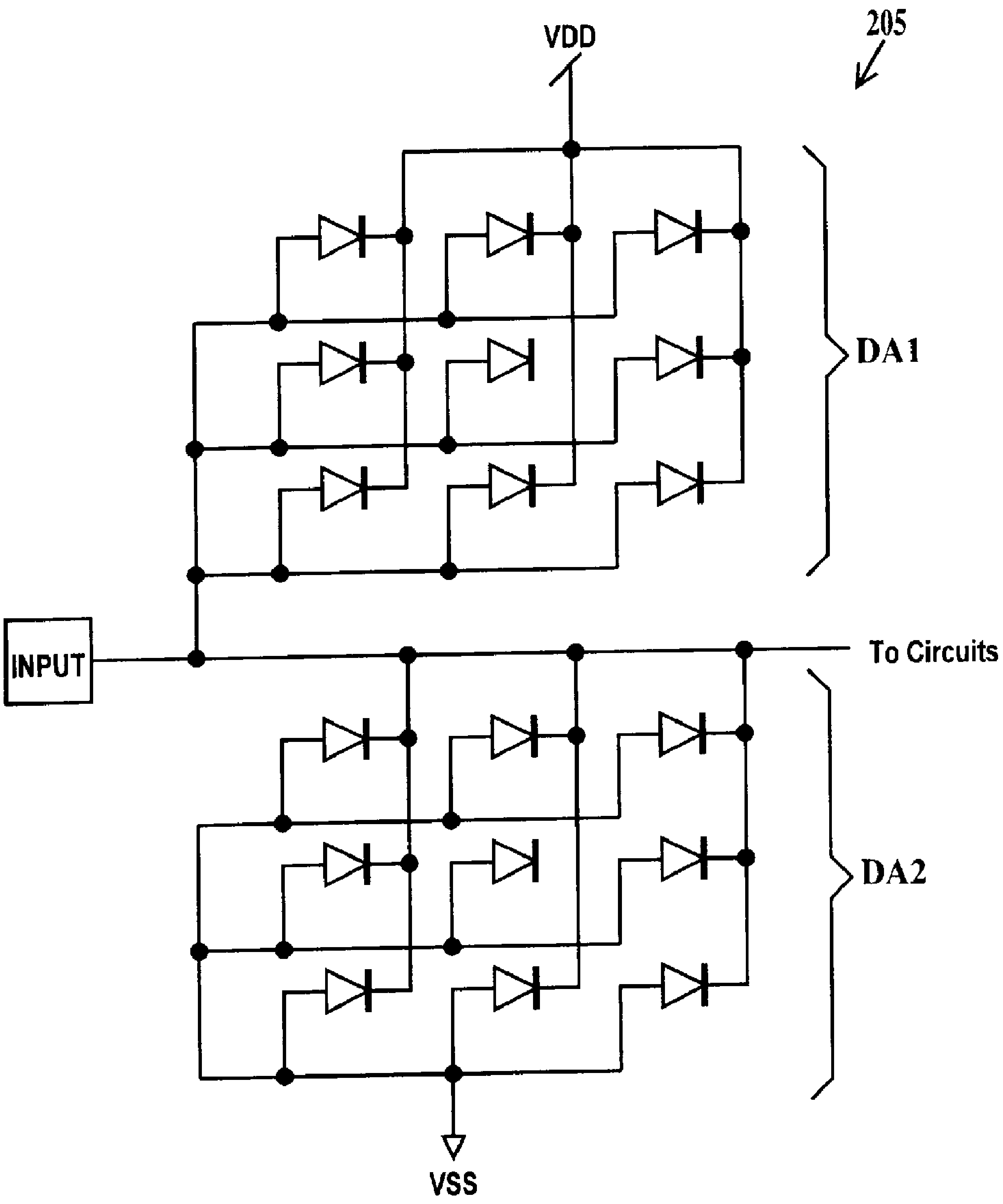
205
VDD
DA1
INPUT
To Circuits
DA2
VSS

FIG. 8

CARBON NANOTUBE DIODES AND ELECTROSTATIC DISCHARGE CIRCUITS AND METHODS

FIELD OF THE INVENTION

The present invention relates to the field of electronic devices; more specifically, it relates to carbon nanotube (CNT) diodes, electrostatic discharge (ESD) circuits using CNT diodes and the method of fabricating the CNT diodes and ESD circuits.

BACKGROUND OF THE INVENTION

The search for ever faster, lower power consuming and thus smaller electronic devices is leading to structures having geometries of width and length smaller than current semiconductor image forming technology can generate. Of particular interest are structures formed from carbon-nanotubes such as quantum dots, CNT wires and CNT field effect transistors (CNTFETs). Circuits constructed using CNTFETs and CNT wires will require ESD protection and structures and methods for providing such protection are virtually unknown. Accordingly, there exists a need in the art to for compatible CNT diodes and ESD circuits for protecting CNT based electronic devices.

SUMMARY OF THE INVENTION

A first aspect of the present invention is a diode, comprising: a p-type single wall carbon nanotube; an n-type single wall carbon nanotube, the p-type single wall carbon nanotube in physical and electrical contact with the n-type single wall carbon nanotube; and a first metal pad in physical and electrical contact with the p-type single wall carbon nanotube and a second metal pad in physical and electrical contact with the n-type single wall carbon nanotube.

A second aspect of the present invention is a diode, comprising: a multiplicity of p-type single wall carbon nanotubes; a multiplicity of n-type single wall carbon nanotubes, each of the p-type single wall carbon nanotubes in physical and electrical contact with one or two of the n-type single wall carbon nanotubes and each of the n-type single wall carbon nanotubes in physical and electrical contact with one or two of the p-type single wall carbon nanotubes; and a first metal pad in physical and electrical contact with every p-type single wall carbon nanotube of the multiplicity of p-type single wall carbon nanotubes and a second metal pad in physical and electrical contact with every n-type single wall carbon nanotube of the multiplicity of p-type single wall carbon nanotubes.

A third aspect of the present invention is a diode array, comprising: a multiplicity of p-type single wall carbon nanotubes spaced apart, extending in a first lengthwise direction and parallel to each other in a first layer; a multiplicity of n-type single wall carbon nanotubes spaced apart, extending in a second lengthwise direction and parallel to each other in a second layer, the first lengthwise direction about perpendicular to the second lengthwise direction; first metal pads in physical and electrical contact with respective p-type single wall carbon nanotubes of the multiplicity of p-type single wall carbon nanotubes and second metal pad in physical and electrical contact with respective n-type single wall carbon nanotubes of the multiplicity of p-type single wall carbon nanotubes; and wherein each p-type single wall carbon nanotube of the multiplicity of p-type single wall carbon nanotubes crosses each n-type single wall carbon nano-tube of the multiplicity of n-type single wall carbon nano-tubes at included angles of greater than zero but no greater than 90 degrees, the p-type single wall carbon nanotubes in physical and electrical contact with the n-type single wall carbon nanotubes where the p-type single wall carbon nanotubes cross the n-type single wall carbon nanotubes.

A fourth aspect of the present invention is an electrostatic discharge circuit, comprising: a first diode according to the diode of the first aspect and a second diode according to diode of the first aspect; a cathode of a the first diode connected to a high voltage terminal of a power source and an anode of the second diode connected to a low voltage terminal of the power source; an input pad connected to the anode of the first diode, to a cathode of the second diode and to circuits to be protected.

A fifth aspect of the present invention is an electrostatic discharge circuit, comprising: a first diode according to the diode of the second aspect and a second diode according to the diode of the second aspect; a cathode of a the first diode connected to a high voltage terminal of a power source and an anode of the second diode connected to a low voltage terminal of the power source; an input pad connected to the anode of the first diode, a cathode of the second diode and to circuits to be protected.

BRIEF DESCRIPTION OF THE DRAWINGS

The features of the invention are set forth in the appended claims. The invention itself, however, will be best understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

FIG. **1**A is a top view and FIG. **1**B is a section view through line **1**B-**1**B of FIG. **1**A of a first CNT diode is according to the present invention;

FIG. **2**A is a top view and FIG. **2**B is a section view through line **2**B-**2**B of FIG. **2**A of a second CNT diode is according to the present invention;

FIG. **3** is a top view of a third CNT diode is according to the present invention;

FIG. **4** is a top view of a fourth CNT diode is according to the present invention;

FIG. **5** is a top view of a CNT diode array according to the present invention;

FIG. **6**A is a top plan view and FIG. **6**B is a section view through line **6**B-**6**B of FIG. **6**A of a fifth CNT diode is according to the present invention;

FIG. **6**C is a cross-sectional view of an alternative arrangement of CNTs illustrated in FIGS. **6**A and **6**B;

FIG. **7** is a first CNT diode ESD circuit according to the present invention; and

FIG. **8** is a second CNT diode ESD circuit according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Carbon nanotubes are closed-cage molecules composed of sp^2-hybridized carbon atoms arranged in hexagons and pentagons. Carbon nanotubes come in two types, single wall nanotubes, which are hollow tube like structures or and multi-wall nanotubes. Multi-wall carbon nanotubes resemble sets of concentric cylinders. The present invention utilizes single-wall carbon nanotubes (SWNT). For the purposes of the present invention, the term carbon nanotube (CNT) denotes a carbon SWNT.

Electrostatic discharge is the sudden and momentary electric current that flows between two objects at different electrical potentials. In electronic devices are particularly sensitive to ESD events occurring on the input and output pins. ESD protection circuits are connected to input and output pins to direct ESD current to, for example, ground rather than allowing the current to propagate to the circuits connected to the pins.

FIG. **1**A is a top view and FIG. **1**B is a section view through line **1**B-**1**B of FIG. **1**A of a first CNT diode is according to the present invention. In FIGS. **1**A and **1**B, a CNT diode **100**A includes a first CNT **105** extending in a first lengthwise direction from a catalytic nano-particle **110** and electrically contacted by a metal contact **115** at an end opposite the end in contact with the catalytic nano-particle. CNT diode **100**A further includes a second CNT **120** extending in a second lengthwise direction from a catalytic nano-particle **125** and electrically contacted by a metal contact **130** at an end opposite the end in contact with the catalytic nano-particle. In FIGS. **1**A and **1**B, CNTs **105** and **120** lie in two different but parallel planes that are both parallel to a plane defined by a top surface of an insulating layer **135**.

Through not shown in FIGS. **1**A and **1**B, contact pad **115** may be formed on the same end of CNT **105** as catalytic nano-particle **110**. Though not shown in FIGS. **1**A and **1**B, contact pad **130** may be formed on the same end of CNT **120** as catalytic nano-particle **125** (see FIGS. **2**A and **2**B). Through not shown in FIGS. **1**A and **1**B contact pad **115** may be formed in a middle region of CNT **105** between its opposite ends. Through not shown in FIGS. **1**A and **1**B contact pad **10** may be formed in a middle region of CNT **130** between its opposite ends. Thus, there are three possible positions for each contact and nine possible combinations of contact positions for both contacts together.

CNTs **105** and **120** cross at an included angle α and electrically contact each other where they cross. CNT diode **100**A is formed on insulating layer **135**, which in turn is formed on a substrate **140**. Catalytic nano-particles **110** and **125** and metal contacts **115** and **130** are in contact with insulating layer **135**. Catalytic nano-particles **110** and **125** are, in one example, iron/cobalt (Fe/Co) or iron/cobalt/nickel (Fe/Co/Ni) when CNTs **105** and **120** are formed by chemical vapor deposition (CVD) from carbon containing gases, e.g. a carbon monoxide (CO) and hydrogen (H_2) mixture.

CNT **105** has a length L**1** and a diameter D**1** and CNT **120** has a length L**2** and a diameter D**2**. L**1** and L**2** are independently between about tens of nm and about a few cm. D**1** and D**2** are independently between about 0.5 nm and about 5 nm. Contact **115** is spaced a distance S**1** from CNT **120** and contact **130** is spaced a distance S**2** from CNT **120**. S**1** and S**2** are independently between about 0.5 nm and about a few cm.

In one example, CNT **105** is a p-type CNT and CNT **120** an n-type CNT. Alternatively, CNT **120** is a p-type CNT and CNT **105** an n-type CNT. CNTs are naturally p-type and there are several methods for making CNTs n-type or more strongly p-type. Contact with palladium (Pd) makes a CNT p-type (majority carriers are holes). Pd has a high work function and physical and electrical contact of a CNT with Pd creates a Schottky barrier that is higher for electrons than for holes. Contact with aluminum (Al) makes a CNT n-type (majority carriers are electrons). Al has a low work function and physical and electrical contact of a CNT with Al creates a Schottky barrier that is higher for holes than for electrons. When CNT **105** is to be n-type and CNT **120** is to be p-type, contact **115** may be formed from Pd and contact **130** from Al. When CNT **120** is to be p-type and CNT **105** is to be n-type, contact **130** may be formed from Pd and contact **115** from Al. It is advantageous, when the doping of CNTs **105** and **120** are by selection of the metal used in contacts **115** and **130**, that distances S**1** and S**2** be as small as possible.

Another method to dope CNTs is by forming a charge transfer complex coating on the CNTs. In one example, CNT may be made n-type by chemically coating it with amine rich polymer, for example polyethylene amine. In one example, the amine rich polymer layer is a monolayer. In one example, CNT made be made more p-type by treating the CNT by forming a charge-transfer complex (that charges the CNT positive) on the surface of the CNT. One method of forming a charge transfer complex on a CNT is by immersion of the CNT in a solution of triethyoxnium hexachloroantimoate $(C_2H_5)_3O^+SbCl_6^-$ followed by rinsing appropriate solvents. When CNTs **115** are doped chemically, contacts **115** and **130** may be formed from metals such as titanium (Ti), tantalum (Ta), copper (Cu) or tungsten (W), though Pd and Al may still be used in combination with chemical coating, Pd on the chemically p-doped CNT and Al on the chemically n-doped CNT. Ti, for example, has an intermediate work function (about 4.33 eV) and physical and electrical contact of a CNT with Ti creates a Schottky barrier that is about equal for holes and electrons.

The angle α formed by the crossing of CNTs **105** and **120** is greater then zero degrees and no greater than 90°.

One example fabrication of CNT diode **100**A is as follows:

(1) Form first catalytic nano-particle **110** on insulating layer **135**;

(2) Grow first CNT **115** by CVD with the reactant gases flowing in a first lengthwise direction;

(3) Form second catalytic nano-particle **125** on insulating layer **135**;

(4) Grow first CNT **115** by CVD with the reactant gases flowing in the a lengthwise direction (the angle between the first and second lengthwise directions being a;

(5) Form first contact **115**; and

(6) Form second contact **130**.

Optionally, after step (2) CNT **115** may be doped by chemical coating, in which case it may be advantageous to form a removable protective coating over CNT **115** prior to step (3). Optionally, after step (4) CNT **120** may be doped by chemical coating, in which case it may be advantageous to form a removable protective coating over CNT **115** prior to forming the doping chemical coating. Optionally, after step (2) CNT **105** may be doped by a first chemical coating and after step (4) CNT **120** may be doped by second chemical coating, in which case it may be advantageous to form a removable protective coating over CNT **115** prior to step (3) and remove a portion of the protective coating where second CNT **120** is expected to cross first CNT **105** prior to forming the second doping chemical coating.

In fabricating CNT diodes **100**D of FIG. **4**, CNT array of FIG. **5** and CNT diode **100**E of FIGS. **6**A and **6**B, which include multiple p-type and multiple n-type CNTs and are described infra, optional steps to remove any purely conductive (as opposed to semi-conductive CNTs) may be added after steps (2) and (4). In a first example, conductive CNTs may be removed by passing a high current (e.g. about 109 A/cm2) through the CNTs. In a second example, conductive CNTs may be removed by subjecting the CNTs to a (e.g. methane) plasma. Additional steps, to protect the CNTs formed in step (2) may be required.

In one example insulating layer **135** is SiO_2 and substrate **140** comprises single-crystal silicon. In a first example, insulating layer **135** and substrate **140** may be a included in an integrated circuit chip which includes devices such as CMOS FETs, bipolar transistors, PN junction and Schottky diodes, thin film and trench capacitors, FET and polysilicon resistors and metal inductors which are wired together along with CNT diode **105**A (or any of CNT diodes **100**B, **100**C, **110**D and **100**E and CNT diode array **150**, all described infra) to form integrated circuits. In a second example, insulating layer **135** and substrate **140** may be included in an integrated circuit chip which includes devices such as CNTFETs, CNT diodes, CNT capacitors, CNT resistors and CNT inductors which are wired together along with CNT diode **105**A (or any of the CNT diodes **100**B, **100**C, **110**D and **100**E and CNT diode array **150**, all described infra) to form integrated circuits. In a third example, insulating layer **135** and substrate **140** may be included in an integrated circuit chip which includes devices such as CMOS FETs, bipolar transistors, PN junction and Schottky diodes, thin film and trench capacitors, FET and polysilicon resistors and metal inductors, CNTFETs, CNT diodes, CNT capacitors, CNT resistors and CNT inductors which are wired together along with CNT diode **105**A (or any of the CNT diodes **100**B, **100**C, **110**D and **100**E and CNT diode array **150**, all described infra) to form integrated circuits. The wiring in either the first, second or third examples may comprise conventional semiconductor wiring techniques such as damascene wires and contacts, CNT wires or combinations thereof.

FIG. **2**A is a top view and FIG. **2**B is a section view through line **2**B-**2**B of FIG. **2**A of a second CNT diode is according to the present invention. In FIGS. **2**A and **2**B, a CNT diode **100**B is similar to CNT diode **100**A of FIGS. **1**A and **1**B, except instead of CNTs **105** and **110** crossing each other at an included angle α, they are parallel to each other (i.e. α=0°) with CNT **120** on top of CNT **105** and they are in electrical contact along a portion of the length of each CNT. In FIGS. **2**A and **2**B, CNTs **105** and **120** lie in a same plane that is perpendicular to the plane defined by the top surface of an insulating layer **135**.

It will be noted that contact **130** contacts CNT **120** in a middle region of CNT between its opposite ends. Contact **130** may contact CNT **120** over the end of the CNT over catalytic nano-particle **125**. Fabrication of CNT diode **100**B is similar to fabrication of CNT diode **100**A described supra.

FIG. **3** is a top view of a third CNT diode is according to the present invention. In FIG. **3**A, a CNT diode **100**C is similar to CNT diode **100**A of FIGS. **2**A and **2**B, except instead of CNT **120** being on top of CNT **105**, they are next to each other and the respective ends opposite catalytic nano-particles **110** and **125** have been bent away from each other. In FIG. **3**, CNTs **105** and **120** lie in a same plane that is parallel to the plane defined by the top surface of an insulating layer **135**. In one example, bending is performed using an atomic force microscope prior to formation of contacts **115** and **130**, Though not shown in FIG. **3**, only one of CNTs **105** and **120** needs to be bent, the other may remain straight. Otherwise, fabrication of CNT diode **100**C is similar to fabrication of CNT diode **100**A described supra.

FIG. **4** is a top view of a fourth CNT diode is according to the present invention. In FIG. **4**, a CNT diode **110**D is similar to CNT diode of FIGS. **1**A and **1**B, except there are a multiplicity of substantially parallel first CNTs **105** and a multiplicity of substantially parallel second CNTs **120** forming a multiplicity of diodes D arranged in an array of columns and rows wired in parallel because a single contact **115** electrically contacts every CNT **105** and a single contact **130** electrically contacts every CNT **120**. In one example, CNTs **105** are about perpendicular to CNTs **120**. The number of CNTs **105** can be as small as one provided the number of CNTs **120** is at least two and vice versa.

FIG. **5** is a top view of a CNT diode array according to the present invention. In FIG. **5**, a CNT diode array **150** is similar to CNT diode **100**D of FIG. **4**, except each CNT **105** is electrically connected to a single contact pad **115** and each CNT **120** is electrically connected to a single contact pad **130**. This allows various diode circuits to be easily wired together into circuits, including ESD protection circuits. Additionally, CNT diode array **150** may be tested and defective individual diodes, rows or columns “marked” as defective and not wired into circuits.

FIG. **6**A is a top plan view and FIG. **6**B is a section view through line **6**B-**6**B of FIG. **6**A of a fifth CNT diode according to the present invention. In FIGS. **6**A and **6**B a CNT diode **100**E is similar to CNT diode **100**B of FIGS. **2**A and **2**B except CNT diode **100**E includes a multiplicity CNTs **105** and **120**. CNTs **105** extend in a lengthwise direction parallel to each other in a first layer that is parallel to the plane defined by the top surface of insulating layer **135** (see FIG. **2**B). CNTs **120** extend in the same lengthwise direction as CNTs **105** parallel to each other in a second layer that is parallel to the plane defined by the top surface of insulating layer **135** (see FIG. **2**B). Each CNT **105** in the first layer is in electrical contact with one or two CNTs **120** in the second layer (forming a CNT **105**/**120** group) along a portion of the length of each adjacent CNT **105** and **120** in the group.

FIG. **6**C is a cross-sectional view of an alternative arrangement of CNTs illustrated in FIGS. **6**A and **6**B. In FIG. **6**C, an alternative arrangement of CNTs **105** and **120** is illustrated where adjacent CNTs **105** are in electrical contact with each other along a portion of the length of each adjacent CNT **105** and adjacent CNTs **120** are in physical and electrical contact with each other along a portion of the length of each adjacent CNT **120**.

FIG. **7** is a first CNT diode ESD circuit according to the present invention. In FIG. **7** an ESD protection circuit **200** includes a first CNT diode D**1** and a second CNT diode D**2**. The cathode of first CNT diode D**1** is connected to VDD and to the anode of second CNT diode D**2** is connected to VSS (e.g. ground). An input pad is connected to the anode of CNT diode D**1** and the cathode of CNT diode D**2**. Integrated circuits to be protected are connected to the input pad.

Diode arrays DA**1** and DA**2** are independently selected from the group of diodes arrays consisting of CNT diode array **100**D and CNT diode array **150** described supra.

FIG. **8** is a second CNT diode ESD circuit according to the present invention. In FIG. **8** an ESD protection circuit **205** includes a first CNT diode array DA**1** and a second CNT diode array DA**2**. The cathodes of each diode of first CNT diode array DA**1** are connected to VDD and the anodes each diode of second CNT diode array DA**2** are connected to VSS (e.g. ground). An input pad is connected to each anode of each diode of CNT diode array DA**1** and to the cathode of each diode of CNT diode array DA**2**. Integrated circuits to be protected are connected to the input pad. Diode D**1** and D**2** are independently selected from the group of diodes consisting of CNT diode **100**A, CNT diode **100**B and CNT diode **100**C described supra.

The description of the embodiments of the present invention is given above for the understanding of the present invention. It will be understood that the invention is not limited to the particular embodiments described herein, but is capable of various modifications, rearrangements and substitutions as will now become apparent to those skilled in the art without departing from the scope of the invention. Therefore, it is intended that the following claims cover all such modifications and changes as fall within the true spirit and scope of the invention.

What is claimed is:

1. A diode, comprising:

said diode comprising an anode and a cathode, said anode comprising a p-type single wall carbon nanotube and said cathode comprising an n-type single wall carbon nanotube, said p-type single wall carbon nanotube in direct and constant physical and electrical contact with said n-type single wall carbon nanotube to form a permanent PN junction;

a first metal pad in physical and electrical contact with said p-type single wall carbon nanotube and a second metal pad in physical and electrical contact with said n-type single wall carbon nanotube; and

wherein said p-type single wall carbon nano-tube has an electron-withdrawing charge transfer complex coating.

2. A diode, comprising:

said diode comprising an anode and a cathode, said anode comprising a p-type single wall carbon nanotube and said cathode comprising an n-type single wall carbon nanotube, said p-type single wall carbon nanotube in direct and constant physical and electrical contact with said n-type single wall carbon nanotube to form a permanent PN junction;

a first metal pad in physical and electrical contact with said p-type single wall carbon nanotube and a second metal pad in physical and electrical contact with said n-type single wall carbon nanotube; and

wherein said p-type single wall carbon nano-tube and said n-type single wall carbon nano-tube are parallel to each other, a portion of the length of the p-type single wall carbon nano-tube and a portion of the length said n-type single wall carbon nano-tube in said physical and electrical contact.

3. A diode, comprising:

said diode comprising an anode and a cathode, said anode comprising a multiplicity of p-type single wall carbon nanotubes and said cathode comprising a multiplicity of n-type single wall carbon nanotubes, each of said p-type single wall carbon nanotubes in direct and constant physical and electrical contact with one or two of said n-type single wall carbon nanotubes and each of said n-type single wall carbon nanotubes in physical and electrical contact with one or two of said p-type single wall carbon nanotubes to form permanent PN junctions; and

a first metal pad in physical and electrical contact with every p-type single wall carbon nanotube of said multiplicity of p-type single wall carbon nanotubes and a second metal pad in physical and electrical contact with every n-type single wall carbon nanotube of said multiplicity of p-type single wall carbon nanotubes.

4. The diode of claim **3**, wherein:

said first metal pad induces holes as the majority carrier in said p-type single wall carbon nanotubes and said second metal pad induces electrons as the majority carrier in said p-type single wall carbon nanotubes.

5. The diode of claim **3**, wherein said first metal pad comprises palladium and said second metal pad comprises aluminum.

6. The diode of claim **3**, wherein each n-type single wall carbon nanotube of said multiplicity of n-type single wall carbon nanotubes has an amine rich polymer coating.

7. The diode of claim **3**, wherein each p-type single wall carbon nano-tube of said multiplicity of p-type single wall carbon nanotubes has an electron-withdrawing charge transfer complex coating.

8. The diode of claim **3**, wherein each p-type single wall carbon nano-tube of said multiplicity of p-type single wall carbon nanotubes crosses each n-type single wall carbon nanotube of said multiplicity of n-type single wall carbon nanotubes at included angles of greater than zero but no greater than 90 degrees, said p-type single wall carbon nanotubes in physical and electrical contact with said n-type single wall carbon nanotubes where said p-type single wall carbon nanotubes cross said n-type single wall carbon nanotubes.

9. The diode of claim **3**, wherein:

each p-type single wall carbon nanotube of said multiplicity of p-type single wall carbon nanotubes extends in a lengthwise direction parallel to each other in a first layer;

each n-type single wall carbon nanotube of said multiplicity of n-type single wall carbon nanotubes extends in said lengthwise direction parallel to each other in a second layer; and

each p-type single wall carbon nanotube in said first layer in physical and electrical contact with one or two n-type single wall carbon nanotubes in said second layer along a portion of the length of each pair of contacting n-type and p-type single wall carbon nanotubes.

10. The diode of claim **3**, wherein:

each p-type single wall carbon nanotube of said multiplicity of p-type single wall carbon nanotubes extends in a lengthwise direction parallel to each other in a first layer, adjacent p-type single wall carbon nanotube of said multiplicity of p-type single wall carbon nanotubes in electrical contact with each other along portions of lengths of each adjacent p-type single wall carbon nanotube;

each n-type single wall carbon nanotube of said multiplicity of n-type single wall carbon nanotubes extends in said lengthwise direction parallel to each other in a second layer, adjacent n-type single wall carbon nanotube of said multiplicity of n-type single wall carbon nanotubes in electrical contact with each other along portions of lengths of each adjacent n-type single wall carbon nanotube; and

each p-type single wall carbon nanotube in said first layer in physical and electrical contact with one or two n-type single wall carbon nanotubes in said second layer along a portion of the length of each pair of contacting n-type and p-type single wall carbon nanotubes.

11. An electrostatic discharge circuit, comprising:

a first diode according to the diode of claim **8** and a second diode according to the diode of claim **3**;

a cathode of a said first diode connected to a high voltage terminal of a power source and an anode of said second diode connected to a low voltage terminal of said power source; an input pad connected to said anode of said first diode, a cathode of said second diode and to circuits to be protected.

12. The diode of claim **3**, wherein said first and second metal pads comprise different metals.

13. The diode of claim **3**, wherein each p-type single wall carbon of said multiplicity of p-type single wall carbon nanotubes is attached to respective first catalytic nano-particles and each n-type single wall carbon of said multiplicity of n-type single wall carbon nanotubes is attached to respective second catalytic nano-particles.

14. The diode of claim **3**, wherein regions of each of said n-type single wall carbon nanotube of said multiplicity of n-type single wall carbon nanotubes and corresponding regions of each of said p-type single wall carbon nanotube of said multiplicity of p-type single wall carbon nanotubes are fixed in physical and electrical contact.

15. A diode, comprising:

said diode comprising an anode and a cathode, said anode comprising a multiplicity of p-type single wall carbon nanotubes spaced apart, each p-type single wall carbon nanotube of said multiplicity of p-type single wall carbon nanotubes extending in a first lengthwise direction and parallel to each other in a first layer and said cathode comprising a multiplicity of n-type single wall carbon nanotubes spaced apart, each n-type single wall carbon nanotube of said multiplicity of n-type single wall carbon nanotubes extending in a second lengthwise direction and parallel to each other in a second layer, said first lengthwise direction about perpendicular to said second lengthwise direction;

first metal pads in physical and electrical contact with respective p-type single wall carbon nanotubes of said multiplicity of p-type single wall carbon nanotubes and second metal pad in physical and electrical contact with respective n-type single wall carbon nanotubes of said multiplicity of p-type single wall carbon nanotubes; and

wherein each p-type single wall carbon nano-tube of said multiplicity of p-type single wall carbon nanotubes crosses each n-type single wall carbon nanotube of said multiplicity of n-type single wall carbon nano-tubes at included angles of greater than zero but no greater than 90 degrees, said p-type single wall carbon nanotubes in direct and constant physical and electrical contact with said n-type single wall carbon nanotubes where said p-type single wall carbon nanotubes cross said n-type single wall carbon nanotubes to form permanent PN junctions.

16. The diode of claim **15**, wherein said first metal pads comprise palladium and said second metal pads comprise aluminum.

17. The diode of claim **15**:

wherein each n-type single wall carbon nanotube of said multiplicity of n-type single wall carbon nanotubes has an amine rich polymer coating; or

wherein each p-type single wall carbon nanotube of said multiplicity of p-type single wall carbon nanotubes has an electron-withdrawing charge transfer complex coating; or

wherein each n-type single wall carbon nanotube of said multiplicity of n-type single wall carbon nanotubes has an amine rich polymer coating and each p-type single wall carbon nanotube of said multiplicity of p-type single wall carbon nano-tubes has a electron-withdrawing charge transfer complex coating.

18. The diode of claim **15**, wherein each of said first metal pads comprise a same first metal, and each of said second metal pads comprise a same second metal, said second metal different from said first metal.

19. The diode of claim **15**, wherein each p-type single wall carbon of said multiplicity of p-type single wall carbon nanotubes is attached to respective first catalytic nano-particles and each n-type single wall carbon of said multiplicity of n-type single wall carbon nanotubes is attached to respective second catalytic nano-particles.

20. The diode of claim **15**, wherein regions of each of said n-type single wall carbon nanotube of said multiplicity of n-type single wall carbon nanotubes and corresponding regions of each of said p-type single wall carbon nanotube of said multiplicity of p-type single wall carbon nanotubes are fixed in physical and electrical contact.

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